REMOTE SENSING ANALYSIS REPORT

Kulalu Area — Sentinel-2 L2A NDVI

Temporal Suitability Analysis & Interpretation

Period of Record: May 2021 – February 2026

BY

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STUDENT ID : ALR41/49147/2025

INTRODUCTION

This study has proceeded from the conviction that the future of land stewardship depends not only on better satellites, more sophisticated algorithms, and more precise environmental models — though all of these matter profoundly and have been developed with rigorous care in the preceding sections. It depends, more fundamentally, on whether the ecological wisdom accumulated across generations of land management — wisdom inscribed in terraced hillsides, encoded in indigenous soil classification schemes, embodied in the hands of farmers who have read their landscape through seasons of abundance and scarcity — can survive the generational transition that is now underway across the climate-stressed landscapes of the developing world. The satellite record tells us, with statistical precision, that the Kulalu rangeland is declining: that a 17% reduction in mean NDVI from 2021 to 2026 represents a genuine degradation trajectory, not a seasonal fluctuation; that the October 2025 NDVI collapse to 0.168 is the lowest value in five years of observation; that the spatial heterogeneity of vegetation cover is increasing in ways consistent with advancing patchwork degradation.

BACKGROUND

The Galana Kulalu Food Security Project (GKFP) is a large-scale government-led irrigation scheme in coastal Kenya, conceived under Vision 2030 to enhance food production in a semi-arid zone. It entails developing 20,000 acres (≈8,100 ha) of pilot farmland (Phase 1) and ultimately up to 1–1.2 million acres (≈400,000–485,000 ha) with irrigation infrastructure, including a proposed 305 million m³ dam on the Galana/Athi River (the "Galana Dam"). The Kenyan government is financing the project using a Public–Private Partnership (PPP) with Selu Ltd. aims to deliver about 720,000 90-kg bags of maize and 160,000 bags of soy per year over 30 years from the 20,000-acre block. The emergence of orbital remote sensing as a tool for environmental monitoring represents one of the most consequential technological developments in the history of land science. Beginning with the LANDSAT programme in 1972 and accelerating dramatically with the European Space Agency's Copernicus constellation — and specifically with the Sentinel-1 Synthetic Aperture Radar (SAR) and Sentinel-2 Multispectral Instrument (MSI) platforms — the capacity to observe land surface dynamics at high spatial resolution, short temporal intervals, and near-zero marginal cost per observation has transformed

the epistemological foundations of environmental monitoring. Where land managers once depended upon the trained eye traversing the landscape on foot, satellite sensors now accumulate systematic, quantitative, spectrally disaggregated records of vegetation condition, soil moisture status, and surface energy balance at spatial resolutions that approach the scale of individual agricultural plots. Among the spectral indices derived from these platforms, two are of particular analytical significance for the environments examined in this study. The Normalised Difference Vegetation Index (NDVI), computed from the ratio of near-infrared to red reflectance as NDVI = (NIR − Red) / (NIR + Red), provides a robust, dimensionless measure of photosynthetically active vegetation density and vigour that has been validated across ecosystems ranging from Arctic tundra to equatorial rainforest (Tucker, 1979; Rouse et al., 1974).

LITERATURE REVIEW

The challenge of engaging young people meaningfully in agricultural science — rather than merely in agricultural labour — requires the construction of educational pathways that connect the intellectual excitement of environmental science to the practical realities of farm management. Remote sensing, with its combination of planetary-scale observation, mathematically sophisticated analysis, and direct relevance to the farm-level decisions that determine household food security, offers exactly the kind of intellectually stimulating, practically grounded educational gateway that can attract scientifically curious young people to agricultural stewardship. The dual-audience design of this study — is itself a methodological experiment in what this educational gateway might look like.

Despite the richness of the global literature on vegetation remote sensing and soil moisture monitoring, several critical scientific gaps remain unresolved within the specific ecological and management context of semi-arid East African smallholder and rangeland landscapes. First, the application of high-resolution (10 m) Sentinel-2 NDVI temporal analysis to Kenyan rangelands — with the forensic statistical rigour demonstrated in the Kulalu study — remains rare in the published literature, which has largely relied on coarser MODIS (250–500 m) or LANDSAT (30 m) products that cannot resolve within-scene spatial heterogeneity at agronomically meaningful scales. Second, the combination of NDMI inferential statistics with SAR-optical data fusion for continuous soil moisture characterisation at the homestead farm scale has not, to the authors' knowledge, been published for Tana-river County or any directly comparable Kenyan ASAL context.

METHODOLOGY

KULALU CAN GROW - BUT ONLY IF THE LAND IS GIVEN STRUCTURE

This report presents a temporal analysis of Normalized Difference Vegetation Index (NDVI) data derived from Sentinel-2 Level-2A imagery over the Kulalu area, spanning May 2021 to February 2026. The dataset comprises 13 cloud-free acquisitions, each sampling 1,080 pixels, enabling a statistically robust characterisation of vegetation dynamics at this location.

Key findings include a baseline mean NDVI of 0.20–0.28 across most observations, consistent with sparse to moderate dryland vegetation typical of semi-arid East African landscapes. A significant anomalous spike on 9 January 2025 (mean 0.473, median 0.492) stands out forensically and warrants careful interpretation. A gradual long-term decline in both mean and median NDVI from 2021 to late 2025 suggests progressive vegetation degradation, with partial recovery evident in early 2026.

The dataset is derived from ESA Copernicus Sentinel-2 Multispectral Instrument (MSI) Level-2A (surface reflectance) imagery. NDVI is calculated from Near-Infrared (Band 8) and Red (Band 4) reflectance using the standard formula:

$$NDVI = (NIR - Red) / (NIR + Red)$$

Values range theoretically from −1 to +1. Negative values typically indicate water, shadows, or bare soil with high red reflectance; values near 0 indicate bare soil; 0.1–0.2 indicates sparse cover; 0.2–0.4 indicates moderate vegetation; and above 0.4 indicates dense, active vegetation.

The 2025-01-09 observation is the single most significant data point in this record and demands forensic scrutiny. Its key statistical signatures are:

a. Mean NDVI of 0.473 — highest in the dataset, 87% above the non-anomalous mean (0.233)
b. Median NDVI of 0.492 — exceeding the mean, indicating a right-skewed distribution with many pixels in the moderate-to-high NDVI range
c. P90 of 0.624 — suggesting that at least 10% of the footprint recorded near-maximum values for this landscape
d. Standard deviation of 0.148 — the highest in the dataset, indicating extreme spatial heterogeneity
e. Max of 0.850 — approaching the theoretical ceiling for vegetated surfaces
f. Min of −0.520 — the most negative minimum in the record, implying surface water or waterlogged pixels

The table below presents all 13 acquisition records with NDVI statistics and vegetation interpretation. The January 2025 anomaly is highlighted in yellow.

Date	Min	Max	Mean	Std Dev	Median	P10	P90	Interpretation
2021-05-20	-0.113	0.684	0.244	0.083	0.238	0.171	0.327	Moderate vegetation / mixed cover
2022-02-19	-0.314	0.602	0.236	0.087	0.228	0.170	0.317	Moderate vegetation / mixed cover
2022-06-04	-0.231	0.673	0.224	0.081	0.217	0.151	0.300	Moderate vegetation / mixed cover
2023-03-01	-0.402	0.621	0.203	0.084	0.191	0.147	0.285	Moderate vegetation / mixed cover
2023-07-14	-0.254	0.721	0.255	0.107	0.237	0.168	0.385	Moderate vegetation / mixed cover
2024-03-25	-0.407	0.775	0.256	0.106	0.249	0.153	0.354	Moderate vegetation / mixed cover
2024-04-29	-0.242	0.734	0.283	0.104	0.288	0.143	0.385	Moderate vegetation / mixed cover
2024-05-29	-0.255	0.752	0.233	0.096	0.235	0.132	0.317	Moderate vegetation / mixed cover

2024-10-16	-0.445	0.740	0.197	0.103	0.191	0.117	0.270	Sparse vegetation / degraded land
2025-01-09	-0.520	0.850	**0.473**	0.148	0.492	0.299	0.624	**Dense vegetation / high biomass**
2025-10-26	-0.414	0.711	0.168	0.091	0.162	0.107	0.235	Sparse vegetation / degraded land
2026-01-11	-0.297	0.693	0.249	0.095	0.249	0.145	0.344	Moderate vegetation / mixed cover
2026-02-13	-0.403	0.668	0.202	0.093	0.195	0.130	0.279	Moderate vegetation / mixed cover

The Kulalu area is best characterised as a moderate-productivity semi-arid rangeland. Its most consistent land-use match is pastoral rangeland or low-input dryland agriculture, particularly in seasonal windows (July–August growing season peaks). The landscape is not currently suitable for high-value permanent agriculture or forestry without significant water harvesting or irrigation infrastructure investment. Following the January 2025 spike, the October 2025 reading (mean 0.168, median 0.162) is the lowest in the entire 5-year record. This pattern — where rapid vegetation greenup is followed by severe die-off — is characteristic of boom-bust vegetation dynamics driven by ephemeral water availability in semi-arid systems. Heavy rainfall saturates soils and triggers rapid growth; as moisture is depleted without replenishment, vegetation rapidly senesces and dies back, often below pre-event levels due to soil nutrient depletion or compaction by floodwaters.

Statistic	Value	Interpretation
Cloud-filtered observations	82	Sentinel-2 L2A observations with cloud cover <=20%

Mean NDVI	0.236	95% CI 0.218-0.253; low-to-moderate dryland vegetation
p10, weakest 10%	0.108	Ecological floor remains low: weak zones are exposed
p90, strongest 10%	0.351	Strong patches prove potential and refugia value
Spatial coefficient of variation	49.0%	Patchy landscape: uniform irrigation will not produce uniform outcomes
Peak/trough ratio	4.16	Pulse-driven system: 0.502 on 2023-12-16 vs 0.120 on 2025-10-03

1. The mean rejects the "wasteland" narrative

The cloud-filtered mean NDVI is 0.236. A one-sample t-test against NDVI 0.20 gives t=4.03, p=0.00013. Kulalu is statistically above a very sparse/stressed threshold. Therefore the evidence does not support dismissing Kulalu as barren. It is alive and conditionally productive.

2. The same mean rejects irresponsible optimism

Tested against NDVI 0.30, Kulalu is strongly below stronger vegetation-cover conditions: t=-7.29, p=1.88e-10. The mean is not statistically consistent with secure, dense, stable cover. Development is possible, but not as an acreage-only engineering promise.

3. The p10 exposes the ecological floor

The mean p10 is only 0.108 with 95% CI 0.095-0.120. The weakest 10% of pixels are close to bare/stressed states. For land-water professors, p10 is not a minor statistic; it is where degradation begins. For youth farmers, it is the part of the farm that fails first.

4. The p90-p10 spread reveals fragmentation

The average p90-p10 spread is 0.244 NDVI units. Spatial stDev averages 0.115, and the spatial coefficient of variation is 49.0%. This is a patchy system. Some zones can carry production, while others require restoration before intensification.

5. Trend mathematics says: opportunity without consolidation

Mean NDVI slope is +0.0107 NDVI/year (p=0.057), close to but not below the conventional 0.05 threshold. p90 improves significantly (+0.0193 NDVI/year, p=0.011), but spatial stDev also rises significantly (+0.0077 NDVI/year, p=0.00006). This indicates polarisation: the best patches are improving faster than the landscape as a whole. Standard deviation values across the dataset

range from 0.081 to 0.148. The consistently high standard deviation (particularly above 0.10 from 2023 onwards) indicates a spatially fragmented landscape with a mixture of vegetated patches, bare ground, and possibly exposed rock or degraded soil. This is consistent with a semi-arid rangeland undergoing patchy degradation, potentially including overgrazing hotspots, active erosion gullies, or bush encroachment in some areas.

Month	n	Mean NDVI
Jan	10	0.357
Feb	8	0.233
Mar	5	0.229
Apr	6	0.287
May	11	0.259
Jun	10	0.216
Jul	5	0.197
Aug	6	0.171
Sep	4	0.156
Oct	8	0.153
Nov	4	0.193
Dec	5	0.273

6. The development equation

Peak greenup (Jul–Aug): Based on the July 2023 and April–May 2024 observations, mean NDVI rises to 0.255–0.283, representing the optimal window for forage biomass assessment and rain-fed crop planting. Post-short-rains (Jan–Feb): The January 2025 event demonstrates that exceptional short-rains seasons can unlock significantly higher productivity, though this cannot be relied upon for planning. Dry season risk (Oct): October observations consistently show the lowest NDVI values (0.197 in 2024, 0.168 in 2025), indicating severe forage deficit periods requiring livestock management planning

Pillar	Statistical justification	Operational action
Water	Required, but not sufficient	Use irrigation scheduling, soil-moisture targets, and drought-window planning
Soil cover	Required by low p10	Mulch, residues, cover crops, reseeding, windbreaks, and erosion-control strips

Drainage	Required by boom-bust spikes	Prevent waterlogging, salinity, crusting, and false greening after wet pulses
Grazing control	Required by fragile dry-season troughs	Protect weak zones; rotate grazing; maintain dry-season ground cover
Monitoring	Required by high spatial variation	Track NDVI, NDMI, Sentinel-1 SAR moisture, rainfall, EC, and field photos

DISCUSSION

The Sentinel-2 NDVI time series for the Kulalu area reveals a landscape under measurable stress, with a long-term declining vegetation trend punctuated by a dramatic and forensically significant anomaly in January 2025. The most plausible explanation for the 2025 spike is an exceptional rainfall or flooding event that temporarily elevated NDVI across the footprint, followed by severe vegetation die-off as conditions returned to deficit. The Kulalu area is best characterised as a moderate-productivity semi-arid rangeland. Its most consistent land-use match is pastoral rangeland or low-input dryland agriculture, particularly in seasonal windows (July–August growing season peaks). The landscape is not currently suitable for high-value permanent agriculture or forestry without significant water harvesting or irrigation infrastructure investment. The area is moderately suitable for pastoral and low-input agricultural use, with clear seasonal windows of productivity, and sustained investment in land rehabilitation, water harvesting, and improved grazing management is required to arrest the long-term degradation trend and improve the landscape's resilience to future rainfall variability.

This analysis is based solely on spectral NDVI data. Findings should be integrated with ground-truthing, soil analysis, socioeconomic surveys, and hydrological modelling for comprehensive land-use planning decisions. The Kulalu area, where Sentinel-2 NDVI analysis reveals a mean vegetation index oscillating between 0.168 and 0.283 across non-anomalous observations — values characteristic of sparse to moderate dryland vegetation — is a landscape perpetually balanced on the threshold between productive cover and degraded bare ground. The October 2024 trough (mean NDVI = 0.197) and the catastrophic October 2025 collapse (mean NDVI = 0.168) following the anomalous January 2025 bloom (mean NDVI = 0.473) represent precisely the boom-bust vegetation dynamics — the sudden pulse of opportunistic growth followed by collapse below pre-event baseline — that characterise semi-arid systems under chronic stress and episodic perturbation.

A mean NDVI of 0.224 places Kulalu within the bare to low vegetation range — consistent with degraded dryland, overgrazed rangeland, dry acacia bushland, or sparsely cultivated small-scale farms. The mean (0.224) and median (0.211) are closely aligned, suggesting relatively uniform low greenness rather than a landscape with productive patches lifting the average. The p10 mean of 0.081 — approaching bare soil — is a particularly diagnostic signal: at least 10% of the Kulalu study area is persistently near-bare at any given usable observation.

The relationship between human communities and the land systems that sustain them is, at its core, a hydrological relationship, every agricultural civilisation in human history has been organised, fundamentally, around the management of water: its capture, its storage, its distribution, and its conservation. The colonial and post-colonial periods introduced agricultural practices and land management philosophies that frequently disrupted these accumulated wisdom systems without replacing them with equivalently effective alternatives. Sedentarisation of historically mobile pastoralist communities, the imposition of fixed field boundaries on landscapes that had been managed through seasonal transhumance, the replacement of diverse indigenous crop varieties with high-input monocultures calibrated for reliably watered environments — these transitions generated the structural vulnerabilities that now manifest as the degradation trajectories visible in the Kulalu NDVI record: the declining mean, the widening spatial heterogeneity, the deepening seasonal troughs.

NDVI exploits the characteristic spectral contrast between the high NIR reflectance of healthy plant canopies — driven by internal mesophyll cell structure and multiple scattering of near-infrared photons — and the low red reflectance resulting from chlorophyll absorption in the 640–680 nm range. This contrast, expressed as a normalised ratio, produces an index whose values rise predictably with increasing green leaf area, photosynthetic capacity, and above-ground biomass, while declining with vegetation stress, senescence, and bare soil exposure. In the Kulalu context, the baseline NDVI range of 0.20–0.28 across most non-anomalous observations is consistent with the spectral signature of sparse to moderate dryland vegetation — Themeda triandra, Chloris gayana, and scattered Acacia species — at typical East African semi-arid rangeland stocking densities. The Kulalu landscape's boom-bust NDVI trajectory, with its spike to 0.473 in January 2025 followed by collapse to 0.168 in October of the same year, is not merely a record of vegetation fluctuation; it is a diagnostic of resilience architecture. The question it poses is whether the landscape retains sufficient soil health, seed bank viability, hydrological function, and ecological connectivity to recover from each cycle of stress and pulse, or whether the accumulating degradation — the declining baseline, the increasing spatial heterogeneity, the deepening dry-season troughs — is progressively eroding the ecological capacities upon which recovery depends.

The environmental problems motivating this study are neither theoretical nor remote. They are inscribed in the satellite record with statistical precision and forensic clarity. In the Kulalu area, a linear regression through non-anomalous NDVI mean values from May 2021 to February 2026 reveals an approximate 17% decline in mean vegetation index — a trajectory that, if sustained,

will progressively erode the landscape's capacity to support both pastoral livelihoods and native biodiversity. The standard deviation of NDVI within individual scenes, consistently above 0.10 from 2023 onwards and reaching 0.148 during the January 2025 anomaly, signals advancing spatial fragmentation of the vegetation cover — the patchy alternation of degraded bare ground, erosion gullies, overgrazing hotspots, and residual vegetation patches that characterises a landscape under intensifying land pressure and unreliable moisture availability.

The difficulty of converting scientific outputs into farmer-legible guidance is not merely a communication challenge; it is a fundamental scientific problem in its own right. The one-sample Mean NDVI slope is +0.0107 NDVI/year (p=0.057), close to but not below the conventional 0.05 threshold. p90 improves significantly (+0.0193 NDVI/year, p=0.011), but spatial stDev also rises significantly (+0.0077 NDVI/year, p=0.00006), This indicates polarisation: the best patches are improving faster than the landscape as a whole — is analytically precise and statistically robust, but it is not, in this form, actionable by a Kulalu smallholder farmer standing in a field with a maize crop at tasselling stage. The translation from this statistical output to the SMS advisory message 'TAHADHARI YA MAJI: Hali ya unyevu ni ndogo. Usiweke mbolea za nitrogen wiki hii. Subiri mvua.' requires a chain of methodological steps — threshold derivation, categorical classification, agronomic calibration, linguistic localisation, delivery architecture design — that constitute a complete scientific programme in themselves.

Systems theory, originating in the foundational work of Ludwig von Bertalanffy (1968) and subsequently developed through the field of cybernetics and general systems research, provides the meta-theoretical architecture within which all other theories in this framework are embedded. Its core contribution is the analytical principle that complex entities — whether ecosystems, hydrological networks, or socio-economic systems — cannot be adequately understood through the analysis of their constituent components in isolation, but only through the study of the relationships, feedback loops, emergent properties, and dynamic behaviours that arise from the interaction of components within a bounded system. The positive feedback between vegetation decline and reduced water infiltration — degraded cover exposes soil surfaces, accelerating runoff and erosion, which further degrades soil structure and reduces infiltration capacity, which further limits vegetation recovery — is exactly the kind of amplifying feedback loop that systems theory predicts and that the declining NDVI baseline of the Kulalu record may be beginning to document.

Resilience theory, as articulated by C.S. Holling (1973) and developed through the Stockholm Resilience Centre's extensive programme of empirical and theoretical research (Folke et al., 2010), provides the conceptual foundation for understanding ecological systems under stress and perturbation. Its central contribution to environmental science is the distinction between engineering resilience — the rate of return to equilibrium following perturbation — and ecological resilience — the magnitude of perturbation a system can absorb before shifting to a qualitatively different state, often characterised by different structure, function, and identity. The Kulalu NDVI record provides a empirical case study in ecological resilience assessment. The

boom-bust dynamics of January 2025 — spike to 0.473 followed by collapse to 0.168 in October — can be interpreted within Holling's adaptive cycle framework as evidence. of a system oscillating between a rapid growth phase (the vegetation flush following exceptional rainfall) and a conservation-to-release transition (the rapid die-off as soil moisture was exhausted) without completing a successful reorganisation phase that would sustain the elevated productivity into subsequent seasons. The baseline NDVI declining from 0.244 in 2021 to approximately 0.202 in 2026 may represent the gradual erosion of the ecological capital — soil organic matter, seed bank viability, soil structural integrity — that would be needed to sustain resilient recovery.

Land degradation in semi-arid environments is a scientific domain marked by both analytical sophistication and persistent methodological controversy. The Drylands Assessment framework of the Millennium Ecosystem Assessment (MA, 2005) established the global extent and economic significance of dryland degradation, while acknowledging the difficulty of distinguishing human-induced degradation from climate-driven vegetation fluctuations at the landscape scale. Darkoh (2003) provided a comprehensive review of land degradation dynamics in sub-Saharan Africa, identifying overgrazing, agricultural expansion onto marginal lands, removal of woody vegetation, and disruption of traditional land management systems as primary anthropogenic drivers.

The engagement of young people in agriculture — particularly in its regenerative and environmentally conscious forms — has emerged as a critical theme in food systems sustainability discourse as the average age of farmers in both sub-Saharan Africa and the developed world continues to rise. FAO (2014) documented the demographic crisis in African agriculture, where the average age of a smallholder farmer exceeds 60 years in many countries, and where rural-urban youth migration is accelerating the pace at which agricultural knowledge systems are depopulated of their next generation of practitioners. Herrero et al. (2021) identified youth engagement in agroecological and regenerative farming as one of the essential transitions required for sustainable global food systems in the coming decades.

CONCLUSION

The most profound gap identified by this review is not scientific or methodological but educational and civilisational: the absence of systematic frameworks for connecting the outputs of contemporary environmental monitoring science to the educational experience of the next generation of land stewards. Young farmers inheriting climate-stressed, ecologically vulnerable landscapes need access to more than traditional knowledge and practical skills; they need the analytical frameworks of remote sensing interpretation, the conceptual tools of ecological systems thinking, and the statistical literacy to evaluate and act upon satellite-derived environmental intelligence. The construction of these educational pathways — across secondary and post-secondary agricultural education, through mentorship and extension systems, through community-based environmental monitoring programmes — represents a frontier that the literature has not yet adequately addressed, and that this study explicitly opens.

The baton must pass, From those who studied the land for decades — who built the terraces, who mapped the moisture, who calibrated the models, who wrote the dissertations — to those who will inherit its consequences: the young farmers standing in fields that are simultaneously ancient and changing, simultaneously documented from orbit and managed by hand. The satellite can see what the eye cannot. The elder can understand what the satellite cannot explain. The young person who learns to hold both of these kinds of knowing simultaneously — who can read an NDVI trend chart and also read the sky, who can interpret a t-statistic and also interpret the colour of the soil after rain — that person is the environmental steward the twenty-first century most urgently needs.